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On the formation of the Magellanic Stream

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Abstract. We use high resolution N-Body/SPH simulations to study the hydrodynamical and gravitational interaction between the Large Magellanic Cloud and the Milky Way. We model the dark and hot extended halo components as well as the stellar/gaseous disks of the two galaxies. Tidal forces distort the LMC's disk, forcing a bar and creating a diffuse stellar halo and a strong warp, although very few stars are unbound from the LMC. Ram-pressure from a low density ionised halo is then sufficient to remove $1.4 \times 10^8 M_\odot$ of gas from the LMC's disk forming a great circle trailing stream around the Galaxy.

1. Introduction

The Magellanic Stream (MS), a trailing filament of neutral hydrogen that originates from the Magellanic Clouds and covers $\sim 100°$ of the Southern Sky, is clearly the result of an interaction between the Clouds and the Milky Way (MW). Althought several models have been proposed for the origin of the MS, no single mechanism appears able to reproduce all the key features of the stream. In particular, tidal stripping models (Lin & Lyndell-Bell 1981; Gardiner & Noguchi 1996; Weinberg 2000) are unable to explain the lack of stars in the Stream and the gradual decrease of the HI column density, moving from the head (close to the Magellanic Clouds) to the tip of the stream. Early ram pressure models (Moore & Davis 1994; Sofue 1994) do not reproduce the amount of gas in the Stream ($\sim 2 \times 10^8 M_\odot$) and are unable to explain the presence of the Leading Arm (Putman et al 1998).

The aim of this work is to study for the first time, the simultaneus effect of gravitational and hydrodynamical forces acting on the Large Magellanic Cloud (LMC) as it moves in the Galactic halo. In particular we are interested in the formation and evolution of the Stream and in the dynamical changes in the internal structure of the LMC due to the interaction with the MW. We neglect the effect of the Small Magellanic Cloud owing to its small mass ($\sim$10% of the LMC).

2. Galactic models

The initial conditions of the simulations are constructed using the technique described by Hernquist (1993). Both the LMC and the MW are multi-component systems with a stellar and gaseous disk, a dark halo and, eventually, a bulge. The density profile of the NFW halo (Navarro, Frenk & White 1997) is adiabatically contracted due to baryonic cooling. The presence of an extended hot ($\sim 10^6$K) halo surrounding the Galactic disk is expected by current models of hierarchical structure formation and seems to be required in order to explain ionisation features associated with HI structures (MS, some high velocity clouds, Outer Spiral Arm, Complex A, Complex B, according to Sembach et al. 2003). Constraints from dynamical and thermal arguments fix the density of the gaseus halo in a range between 10^{-5} and 10^{-4}cm^{-3} at a distance of 50 kpc from the Galactic Center. The density beyond this radius is still unknown. We model the hot halo of the MW with a spherical distribution of gas that traces the dark matter profile and is in hydrodynamical equilibrium inside the Galactic potential. This ionised gas has a mean density of 2×10^{-5}cm^{-3} within 150 kpc and a temperature $\bar{T} \sim 10^6$ K. The rotation curves and the main parameters of the LMC model are shown on the left side of Figure 1. The masses and the scale lengths are selected in order to reproduce observational constraints from Kim et al. 1998 and van der Marel 2002, while for the MW we adopt the favoured model of Klypin, Zhao & Sommerville 2002.

3. Simulations

The LMC is now at $\sim$ 50 kpc from the Galactic Center and kinematical data imply that it is close to the perigalacticon. We wish to simulate the past couple of orbits of the LMC whilst ending up with the satellite in the same position and inclination as observed today. Using several low resolution test simulations we are able to achieve an orbit that leads to the present position and velocity of the LMC accounting for the orbital evolution induced by the combined effect of dynamical friction and tidal stripping (Colpi, Mayer & Governato 1999). The result is an orbit with the last apo/peri ratio 2.5:1, a perigalacticon distance of $\sim$ 45 kpc and a period of 2 Gyrs. In choosing the initial inclination and position of the line of nodes we make the approximation that they do not change during the interaction. In particular we adopt the values from van der Marel 2002: respectively $i = 34.7°$ and $\Theta = 129.9°$.

We follow the interaction between the MW and the LMC for 4 Gyrs, using GASOLINE a parallel tree-SPH code with multistepping (Wadsley, Stadel & Quinn 2003). The high resolution runs have 2.46×10^6 particles, of which 3.5×10^5 are used for the disks and 5×10^5 for the hot halo of the MW. The gravitational softening is set equal to 0.5 kpc for the dark and gaseus halos, to 0.1 kpc for stars and gas in the disk and bulge components. The right side of Figure 1 shows the loss of gas and stars (calculated using SKID, Stadel 2001) from the LMC disk during the last 4 Gyrs. The amount of stripped stars is negligible compared with the stripped gas. A pure tidal stripping model would remove similarly small amounts of both components. The large amount of stripped gas is due primarily

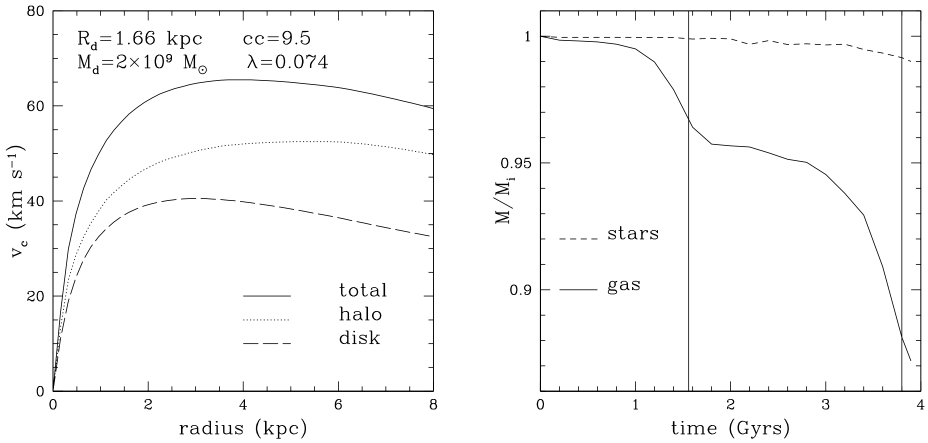

Figure 1. Left: Rotation curves for the LMC model. On the top disk mass and scale length, concentration and spin parameter are indicated. Right: Fraction of bound stars and gas during the last 1.5 orbits. The vertical solid lines represent the apogalactica.

to ram-pressure stripping: the rate at which gas is lost increases as the LMC approaches perigalacticon (the solid vertical lines in the plot), corresponding to higher densities of the ionised halo and to higher velocities of the satellite along the orbit. Gas is stripped starting from the first passage at the perigalacticon, forming a stream perpendicular to the Galactic plane (left side of Figure 2), with a final mass of $1.4 \times 10^8 M_\odot$. The column density distribution gradually decreases along the length of the stream, reaching $3 \times 10^{18}\mathrm{cm}^{-2}$ at 100° from the LMC. This decrease in density by nearly two orders of magnitude along the stream is a remarkable success for the ram-pressure scenario - tidal models generically produce streams with surface densities that fall off much more slowly. From Figure 2 it is evident that part of the material stripped from the satellite during the last orbit is falling to the Galactic center in the Northern Galactic hemisphere. Our simulations predict that the MS forms a great circle. More speculatively, the material stripped several Gyrs ago lies in the same place on the sky as the observed leading arm feature. The right side of Figure 2 shows the stripped stars: there is no well defined stellar stream, since only $10^7 M_\odot$ of stars are stripped from the disk mainly during the last perigalacticon, when the satellite is ≈ 50 kpc from the Galactic center. The Galactic disk is unperturbed by the interaction, but the LMC's disk suffers a strong warp that wraps 180 degrees around the LMC forming a large spheroid with a tidal radius of 25 kpc. As a consequence of the resulting asymmetrical potential and distorted stellar disk, it is easier to strip more gas from the LMC's disk since the gravitational restoring force is weaker. Thus even a low density gaseous Galactic halo is able to remove a significant amount of gas from the LMC. Within the first 1.6 Gyrs from the beginning of the simulation tidal forces drive bar formation in the central 4 kpc of the satellite galaxy. The LMC's disk becomes elongated (with an axial ratio 1:2) in a direction close to the one of the Galactic center and perpendicular to the Stream.

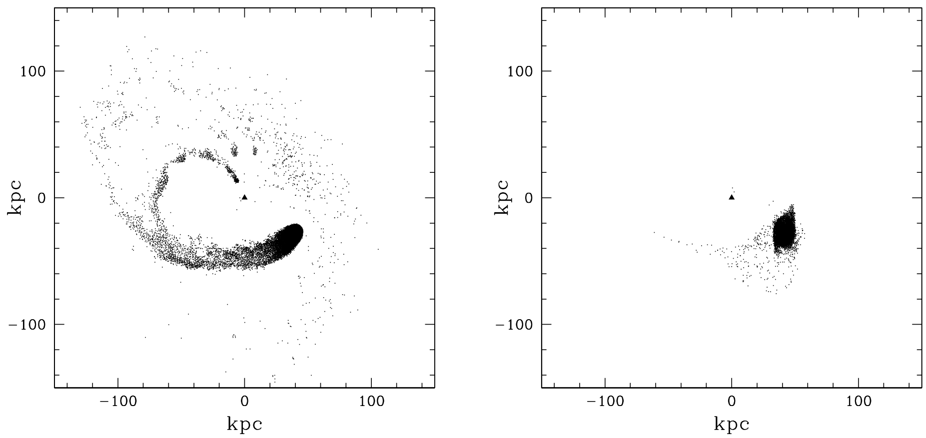

Figure 2. Final distribution of gas (left) and stars (right) from the LMC disk in a plane perpendicular to the Galactic disk.

4. Conclusions

1) Many of the features observed in the LMC's stellar disk can be explained through the tidal interaction with the MW.
2) Tidal forces are not able to strip a significative amount of stars from the satellite galaxy, but they produce a stellar spheroid around the disk.
3) A continuous gaseus stream is produced by ram pressure stripping from a low density gaseous Galactic halo. The morphology of the stripped gas resembles the Magellanic Stream.
4) Part of the gas stripped during the first passage at the perigalacticon is now close to the satellite. Is this gas able to explain the Leading Arm feature?

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